

The Uncertainties in the Age of Globular Clusters from Their Helium Abundance and Mass Loss

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Abstract

The age of globular clusters inferred from observations depends sensitively on assumptions such as the initial helium abundance and the mass loss rate. A high helium abundance (e.g., $Y \approx 0.28$), as well as an inclusion of helium diffusion and oxygen-enhancement in stellar models, can lower the current age estimate for metal-poor globular clusters from 14 ± 1.5 Gyr to about 11 ± 1 Gyr, significantly relaxing the constraints on the Hubble constant, allowing values as high as 60 km/sec/Mpc for a universe with the critical density and 90 km/sec/Mpc for a baryon-only universe. The uncertainties of a high helium abundance and an instability strip induced mass loss near the turn-off in globular clusters are discussed. Ages lower than 10 Gyr are not possible even with the operation of both of these mechanisms unless the initial helium abundance in globular clusters is > 0.28 , which can hardly be accommodated by indirect inferences of helium abundances in globular clusters.

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I. INTRODUCTION

The latest estimate of the age of globular clusters (GCs) is 14.1 ± 1.5 Gyr averaging over 24 globular clusters [1], or 15 ± 1.5 Gyr for oldest GCs [2]. This sets a lower bound on the age of the universe which severely constrains H_0 , the Hubble constant, for a Λ (the vacuum energy density)=0 Friedman-Robertson-Walker cosmology. For example, if the age of the universe is 15 Gyr, for Ω (the ratio of the density of the universe to the critical density)=1, the Hubble constant H_0 must be less than 45km/sec/Mpc [1]; while for a baryonic universe where $0.01/h^2 < \Omega < 0.015/h^2$ (with $h = H_0/100\text{km/sec/Mpc}$) as constrained by Big Bang Nucleosynthesis [3,4], $H_0 \lesssim 70\text{km/sec/Mpc}$. Currently dynamic measurements of the density of the universe favor $\Omega > 0.3$ [5], which yields $H_0 \lesssim 55 \text{ km/sec/Mpc}$. Direct measurements of the Hubble constant, however, yield values that range widely from 40km/sec/Mpc to 100 km/sec/Mpc [6].

A reconciliation of the direct measurements of the Hubble constant and that inferred from the age of the globular clusters may well require not only improvements of the distance scale systematics but also continued investigation of the implicit assumptions in the inferred age of globular clusters. Otherwise, the conflict may prove to be an insurmountable problem for $\Omega = 1$, $\Lambda = 0$ cosmology models.

It is noted that the estimate of the age depends sensitively on many uncertain aspects of globular clusters, such as the actual turn-off luminosity (distance) determination, the metallicity, the oxygen to iron ratio, helium diffusion in stars, the initial helium abundance, and an instability strip induced mass loss inferred from lithium observations of stars [7]. The uncertainties of the turn-off luminosity, the metallicity and the oxygen to iron ratio have been widely discussed in the literature [9–11], and has been included in the current age estimate of 14.1 ± 1.5 Gyr [1]. The helium diffusion in stars is also estimated to lower the age of GCs by 5%–15% [12–14]. Uncertainties in the initial helium abundance and the mass loss rate of stars near the turn-off point have been explored previously [7,8]. But since these systematic uncertainties should not be added in quadrature like statistical uncertainties, a

full exploration including uncertainties in the helium abundance, mass loss, helium diffusion and oxygen-enhancement is essential to assess their influence on the age estimate of globular clusters.

The aim of this paper is to explore the uncertainties in the helium abundance and mass loss in globular clusters both theoretically and observationally, and calculate the age estimates for globular clusters under these uncertainties as well as oxygen-enhancement, using stellar models with helium diffusion. Section 2 discusses the methods used in dating the age of globular clusters and their dependence on various parameters. In this section, we also present our formula that relates the age of globular clusters to their parameters, based on our stellar models with helium diffusion. Section 3 discusses uncertainties in the current inferences of the helium abundance in globular clusters due to uncertainties in both stellar evolution theory and stellar observations. In particular, it argues that the current inferences may allow a helium abundance as high as 0.28 in globular clusters, which is significantly higher than the primordial value of 0.24. Section 4 provides possible scenarios that can enhance the helium abundance in globular clusters from the primordial value to a higher one. Section 5 then discuss a possible instability strip induced mass loss near the turn-off region of globular clusters, and its effect on the luminosity functions (LFs) of globular clusters and their age. The observed luminosity function of globular clusters thus constrains the size of the mass loss effect. The effect of a mass loss combined with a high helium abundance is also investigated. Section 6 summarizes the previous sections and concludes that by considering the uncertainties in the helium abundance and mass loss in globular clusters, as well as helium diffusion and oxygen enhancement, the age of metal-poor clusters can be as low as 11 ± 1 Gyr. But ages lower than 10 Gyr for metal-poor clusters cannot be consistent with observed properties of globular clusters.

II. AGE DATING OF GLOBULAR CLUSTERS

Two methods are commonly used to estimate the age of a globular cluster (see review of ref. [15]). One is to fit theoretical isochrones (temperature-luminosity curves for stars of a given age) to the shape of a globular cluster on the observed color-magnitude diagram, using a distance modulus determined from fitting either a zero age main sequence (ZAMS) or a zero age horizontal branch (ZAHB). In the fitting, it is necessary to transform a temperature-luminosity diagram of theoretical isochrones into a color-magnitude diagram with an interstellar reddening correction [11]. Besides the uncertainties mentioned in the introduction, this method is very sensitive to the transformation between the luminosity-temperature diagram and the color-magnitude diagram, the fiducial sequence of globular clusters extracted from their scattered color-magnitude diagram, the subjectivity in fitting isochrones to the fiducial sequence, and the effectiveness of a constant mixing length in describing the convection. It also depends sensitively on the adopted interstellar reddening if using ZAMS fitting to obtain distances.

The difficulty in improving the fitting method lies mainly in the fact that the color of both observed GCs and theoretical isochrones on the color-magnitude diagram is hard to determine precisely. The color of observed GCs depends on the interstellar reddening which can be very uncertain; while the color of isochrones is sensitive to the treatment of convection in stellar models. Figure 1 shows isochrones with similar parameters but different mixing lengths (parametrized by α , the ratio of the mixing length to the pressure scale height) in the convection zone. Both isochrones have a similar turn-off luminosity, but the color shift due to a different choice of α is manifest, especially on the upper subgiant and the red giant branch of isochrones. Although the uncertainty in choosing different mixing lengths may be partially resolved by calibrations of ZAMS stars [16], it still persists since mixing lengths may change in different evolution phases, such as the subgiant branch and the red giant branch.

A method that is not sensitive to the color determination is to relate the age of a GC

with the difference in luminosity between the GC's turn-off point and horizontal branch, regardless of its detailed morphology. Such a relation has been shown by Iben and Renzini [17] to be

$$\log\left(\frac{\text{Age}}{\text{yr}}\right) = 8.497 - 1.88(Y - 0.24) - 1.44(Y_{\text{HB}} - Y) - 0.088 \log Z + 0.41(M_{\text{bol}}^{\text{TO}} - M_{\text{bol}}^{\text{RR}}), \quad (1)$$

where Y is the initial helium abundance of GCs, Z is their metallicity, Y_{HB} is the helium abundance at the envelope of the HB stars, $M_{\text{bol}}^{\text{TO}}$ and $M_{\text{bol}}^{\text{RR}}$ are the bolometric magnitudes of the turn-off point and the RR Lyrae stars respectively. The coefficients in the equation have been refined over the years, but the resultant age hasn't changed by more than 25%. For example, a similar relation based on Sandage's calibration of RR Lyrae stars [18] and the oxygen-enhanced isochrones of Bergbusch and Vandenberg [11], assuming $Y \approx 0.24$, is [1]

$$\log\left(\frac{\text{Age}}{\text{yr}}\right) = 8.773 + 0.017[\text{Fe}/\text{H}] + 0.39(M_{\text{v}}^{\text{TO}} - M_{\text{v}}^{\text{RR}}), \quad (2)$$

where M_{v} denotes the visual magnitudes. Equation (2) tends to yield an age that is $\sim 20\%$ lower than eq. (1) for metal-poor clusters. The method of relating the age of GCs and their turn-off luminosities is independent of the interstellar reddening, the subjectivity of fitting isochrones to the observed GC sequence and the mixing length adopted in stellar modeling. It still suffers from the uncertainties mentioned in the introduction.

In order to test the sensitivity of GC ages to the helium abundance for stellar models with helium diffusion, we constructed a series of models between $0.60M_{\odot}$ and $0.90M_{\odot}$, with an interval of $0.05M_{\odot}$. Their metallicities are chosen to be $Z=0.0002$ ($10^{-2}Z_{\odot}$), 0.0006 and 0.002 . The helium abundance of the models is set to be 0.24 and 0.28 . We adopted a mixing length of $\alpha = 1.69$. All models were started as pre-main sequence objects on the Hayashi track, and evolved to helium flash, or 25 Gyr old (which is enough for GCs around 15 Gyr old), whichever comes earlier. We used Livermore opacity tables for temperatures above 6000K [19], and Los Alamos opacities below 6000K [20]. The code we used is based on

Dearborn’s stellar code [21], with an inclusion of helium diffusion using the prescription of Bahcall and Loeb [22]. From these models, we found that

$$\log\left(\frac{\text{Age}}{\text{1yr}}\right) = 8.11 - 0.12 \log Z + 0.40 M_{\text{bol}}^{\text{TO}} - 0.80(Y - 0.24). \quad (3)$$

Our models agree fairly well with previous helium diffusion calculations [12–14].

Since the helium diffusion affects little the evolution of HB stars due to their short life span, we can just take the result of HB calculations without including helium diffusion [23,24]:

$$M_{\text{RR}}(\text{bol}) = 0.943 - 3.5(Y_{\text{HB}} - 0.30) + 0.183 \log Z. \quad (4)$$

Combining eq. (3) and (4), we get

$$\log\left(\frac{\text{Age}}{\text{1yr}}\right) = 8.57 - 0.047 \log Z - 2.20(Y - 0.24) - 1.40(Y_{\text{HB}} - Y) + 0.40(M_{\text{bol}}^{\text{TO}} - M_{\text{bol}}^{\text{RR}}). \quad (5)$$

This result compared with non-diffusion calculations based on the same code [7] lowers the age of metal-poor clusters by about 8%. It yields ages that are generally 15% to 25% lower than eq. (1), depending on Z .

We couldn’t obtain oxygen-enhanced models with Livermore opacity tables. But it has been shown that for Los Alamos opacity tables, oxygen-enhanced models with a metallicity Z (deduced from $[\text{Fe}/\text{H}]$ only) can be approximated by standard solar-scaled abundance models with a metallicity Z_{eff} , provided that [25]

$$Z_{\text{eff}} = (0.64f + 0.36)Z, \quad (6)$$

where f is the enhancement factor of oxygen. If this also holds true for Livermore Opacity Tables, oxygen-enhanced models will yield the same equation as eq. (5), as long as Z_{eff} is substituted for Z . Commonly f is taken to be 3 to 5 in metal poor clusters [10], therefore $Z_{\text{eff}} \approx 3Z$, which will further lower the age estimate from eq. (5) by about 5%.

$Y_{\text{HB}} - Y$ is estimated to be 0.01–0.02 in models without helium diffusion [17], and -0.005 – 0.005 in helium diffusion models [12,13,26]. Therefore a strong dependence of the age on the helium abundance Y is manifest in both eq. (1) and eq. (5).

It is conventionally assumed that $Y \approx 0.24$ in GCs [1,11], in agreement with the observed primordial helium abundance $Y = 0.235 \pm 0.01$ [27] and the prediction of Big Bang Nucleosynthesis [3,4]. But both eq. (1) and eq. (5) show that a higher Y (but $\lesssim 0.28$) and can significantly reduce the age estimate of GCs. For example, a Y of 0.28 will reduce the age by as much as 20% with respect to a Y of 0.24, according to eq. (1) and (5). Even a Y of 0.26 will lower the current age estimate by 10%.

Determining the age of GCs with the isochrone fitting method has a similar Y sensitivity as in eq. (1) or (5) if a distance modulus from ZAHB fitting is used. If a distance from ZAMS fitting is used in the isochrone fitting, the effect of a higher Y in GCs on their age is not easy to quantify. Figure 2 shows the comparison of a $Y = 0.28$ isochrone and $Y = 0.24$ isochrones in fitting the fiducial sequence of NGC6397 (adopted from [28]). Both isochrones include helium diffusion but don't include oxygen-enhancement due to the adoption of Livermore opacities in most of the temperature range, and have a $Z = 0.0002$. NGC6397 is believed to have $[\text{Fe}/\text{H}] = -1.91$ [1]. The reddening and distance modulus adopted for the cluster are 0.11 and 12.35 for the $Y = 0.24$ isochrones, 0.14 and 12.45 for the $Y = 0.28$ isochrone. The distance modulus estimated from calibrations of RR Lyrae stars is about 12.5 [28]. Fig. 2 shows that while NGC6397 has an age of ~ 15 Gyr when fit with the $Y = 0.24$ isochrones, it is only ~ 12 Gyr old when fit with the $Y = 0.28$ isochrones. This is in general agreement with eq. (5) from which a Y of 0.28 yields an age 20% younger than a $Y = 0.24$.

III. THE MEASUREMENT OF HELIUM ABUNDANCES IN GCS

The surface temperatures of stars in globular clusters are too cool to have detectable helium lines. Therefore, the Y in GCs cannot be measured directly from spectra of stars. Instead, Y is indirectly determined from comparisons between certain theoretically Y de-

pendent parameters of GCs deduced from stellar models and the measurement of such parameters from GC observations.

One such parameter is the relation between the effective temperature and period of RR Lyrae stars at the blue edge of the instability strip [29]. Comparison of this relation between canonical stellar models (i.e., no rotation, no diffusion, no mass loss, etc) and observations yields $Y_{\text{HB}} = 0.27 \pm 0.04$ [30]. A similar comparison is done to the A parameter, which relates the effective temperatures and periods of general RR Lyrae stars [31]. This comparison usually yields a high Y_{HB} of 0.26–0.33 [31], and leads to an anti-correlation between the metallicity of a cluster and its helium abundance, which can hardly be explained with any chemical evolution theories [31,32]. This anti-correlation problem may vanish if one assumes a varying core mass in HB stars due to non-canonical effects (for example, rotation [33]), and/or a varying CNO abundance [31]. Both of these comparisons, however, involve the determination of the effective temperatures of RR Lyrae stars, which, as mentioned above, cannot be confidently inferred from their observed colors due to the uncertainty in the interstellar reddening and stellar modelling.

Another parameter is R , which is the ratio of the number of stars on the horizontal branch to the number of stars on the red giant branch with luminosities higher than the mean luminosity of RR Lyrae stars. Stellar models show that R is very sensitive to Y_{HB} and thus Y . Canonical stellar models yield a R - Y relation [24,34]:

$$Y = 0.186 + 0.37 \log R, \quad (7)$$

assuming $Y_{\text{HB}} - Y \approx 0.02$, a result from canonical models that exclude helium diffusion. Eq. (7) yields an average Y of 0.23 ± 0.02 for 15 GCs [24]. However, if other non-canonical effects such as rotation operate in GC stars to increase M_c , the helium core mass of HB stars, estimate of Y can be higher than canonical values. For example, a core rotation rate of 2×10^{-4} rad/s, a typical main sequence value, will increase M_c by $0.03 M_{\odot}$ [30], and increase the estimate of Y from the R comparison by 0.01, since [34]

$$dY/dM_c = 0.4. \quad (8)$$

Assuming a larger and varying M_c , Caputo *et al.* obtained an average Y of 0.24 ± 0.01 when combining the R -method and the A -method [34]. Furthermore, as we have shown, if we include helium diffusion, $Y_{\text{HB}} - Y$ will be only about 0.005. In addition, M_c will be slightly increased by $0.005M_\odot$ with respect to that of canonical models due to the helium settlement into the core, which results in a 0.002 increase in Y_{HB} . The resultant Y will therefore be 0.02 higher than the value inferred from eq. (7), just from the inclusion of helium diffusion in stellar models alone.

The luminosity spread of the horizontal branch serves as another parameter that can be used to determine the helium abundance. A larger Y_{HB} yields a broader luminosity spread among the horizontal branch stars, according to HB models [23]. Such comparisons for 47 Tuc and M15 suggested a Y_{HB} close to 0.24 [35,36]. But again, possible systematic variations in M_c unaccounted for in canonical models may affect the result. For example, to bring the Y values from the A -method and the R -method into agreement, it is shown by Caputo *et al.* that M_c in M15 has to be increased by $0.04M_\odot$ relative to its canonical value [34]. According to the calculations of Sweigart and Gross [23], a $0.04M_\odot$ increase in M_c will narrow the predicted luminosity spread of a horizontal branch appreciably and thus allow a higher Y_{HB} given an observed luminosity width of HB.

A Δ parameter is also proposed to determine Y , where Δ is defined as the magnitude difference between RR Lyrae stars and the main sequence at $(B - V)_0$ (the corrected $B - V$ color) = 0.7 [37]. Comparison with the measured Δ yields a Y of 0.2 to 0.3. This method depends on the determination of the metallicity of GCs, the color determination [37], and hasn't accounted for effects such as helium diffusion.

Despite these many methods of determining Y for GCs, a statistically sound upper limit on Y is lacking. However, a $Y > 0.28$ is very hard to reconcile with most of the above determinations, especially the comparisons of the R parameter and the luminosity spread of HB, even when aforementioned non-canonical effects are taken into account.

A maximal helium abundance of 0.28 in GCs seems also to be consistent with that inferred from luminosities of the HB stars. Y_{HB} is related with the luminosity of RR Lyrae

stars by eq. (4) in canonical models. Current calibrations of the visual magnitude of RR Lyrae stars yield a 0.2–0.3 magnitude spread for different methods, and an uncertainty of 0.2 magnitude within each method [2,18,38,39]. which translates into a 0.06 uncertainty in Y_{HB} . In other words, a Y of 0.28 can be easily accomodated for individual clusters, given a primordial value of 0.24. It should be noted that the observation of field RR Lyrae stars in the disk of the galaxy may not serve a valid constraint on Y_{HB} in globular clusters if only stars in GCs are enriched in helium. For example, RR Lyrae stars in seven Large Magellanic Cloud clusters are on average 0.28 magnitude brighter than field RR Lyrae stars [2], which can be consistent with an enhancement of helium abundances only in globular clusters.

IV. SCENARIOS TO ENHANCE THE HELIUM ABUNDANCE IN GCS

A helium abundance higher than the primordial value Y_{p} in GCs is possible to achieve under certain scenarios. The simplest scenario is the enrichment by the first generation supernovae (SNe) [7,40] Measurements of low metallicity HII regions in irregular galaxies and extragalactic HII regions showed that their helium abundance Y correlates with their oxygen abundance $[\text{O}/\text{H}]$ by [27,41]

$$Y \approx Y_{\text{p}} + 130[\text{O}/\text{H}] \quad \text{for} \quad [\text{O}/\text{H}] \lesssim 2.5 \times 10^{-4}, \quad (9)$$

i.e., $dY/dZ \approx 6$. For GCs with $[\text{Fe}/\text{H}]=-1$, their oxygen abundances are about 1/3 of the solar value [9], or $[\text{O}/\text{H}] \approx 3 \times 10^{-4}$. If GCs follow the same helium-oxygen correlation as those low metallicity HII regions, they have $Y \approx 0.27$, which is significantly above the primordial value. Of course, it is debatable whether GCs follow the same Y - $[\text{O}/\text{H}]$ relation as low metallicity HII regions, although both of them have similarly low metallicities. The sun, on the other hand, has $Y \approx 0.28$ and $[\text{O}/\text{H}]=8 \times 10^{-4}$, which would require a different relation $Y \approx Y_{\text{p}} + 60[\text{O}/\text{H}]$ (i.e., $dY/dZ = 3$). Therefore, solar-type disk stars must have had quite a different chemical history from low metallicity gases, like those of GCs and HII regions. It is worth noting that VandenBerg, Bolte and Stetson [42] found a 2–3 Gyr

age spread among GCs with $[\text{Fe}/\text{H}] > -1.6$ and no significant age spread among GCs with $[\text{Fe}/\text{H}] < -1.6$. If an enhancement in the helium abundance correlates with an increase of metallicity in GCs, as suggested above, the age spread among metal-rich GCs may be explained at least in part by the different enrichment of helium in different clusters.

Exotic models, such as Pop III stars [43,44], may enrich helium but not heavier elements. It is calculated that if the oxygen cores of these Pop III stars are larger than $\sim 100M_{\odot}$, the cores will collapse completely into blackholes without ejecting heavy elements. However, processed helium in Pop III stars can be deposited into the interstellar medium through mass loss and mixing of Pop III stars. The maximal amount of helium enrichment is $\Delta Y = 0.17$ for an initial helium abundance of 0.24, if all gas is processed once in Pop III stars [43,44]. Therefore, in order to enhance the helium abundance in a $10^6 M_{\odot}$ cloud from 0.24 to about 0.28, at least $2.5 \times 10^5 M_{\odot}$ gas has to be processed through Pop III stars. This requires quite a different mass function from the M^{α} power law with $\alpha = -2.35$ observed today [45]. Since the metallicity of the cloud is low, the required mass function could have $\alpha \gtrsim -0.5$, so that there were no more than ~ 100 SNe in a $10^6 M_{\odot}$ cloud that would deposit metals into the cloud.

An enhancement of the helium abundance may also arise during the formation of globular clusters due to the difference in the first ionization energy between the hydrogen and the helium (13.6eV vs. 24.6eV). In certain GC formation scenarios, this difference may enable helium to recombine while hydrogen are still heavily ionized. As a result, helium may have a slower sound speed than hydrogen and is therefore more prone to gravitational collapse.

One class of models of forming GCs, first proposed by Peebles and Dicke [46], argues that GCs form from primordial baryon density fluctuations after recombination, which have a Jeans mass of a typical GC mass, $10^6 M_{\odot}$. According to the standard recombination picture of the universe, hydrogen recombined at $T \sim 3000\text{K}$ (redshift $z \sim 1000$) [47] while helium recombined at $T \sim 10^4\text{K}$ or $z \sim 3000$ (inferred from Fig. 5 of ref. [48]). In between $z \sim 1000$ and 3000 there existed a period when helium recombined and primarily interacted with atoms, ions and electrons, and hydrogen were still mostly ionized and primarily interacted

with background photons. Therefore helium can collapse earlier than hydrogen due to its lower sound speed.

In the period after helium recombination and before hydrogen recombination, the helium falls quickly into the potential well of dark matter, following the density fluctuation of dark matter [49]. As hydrogen recombines, the density fluctuations in the hydrogen and the helium begin to grow jointly. The overdense region, however, already has an enhanced helium abundance from the in-fall of helium early on. Assuming the density fluctuation in dark matter at $z \sim 1000$ to be $\delta\rho/\rho$ and the primordial helium abundance $Y_p = 0.24$, the enhanced helium abundance in the overdense region at $z \lesssim 1000$ is [7]

$$Y = \frac{Y_p(1 + \delta\rho/\rho)}{Y_p(1 + \delta\rho/\rho) + 1 - Y_p} \approx 0.24(1 + 0.76\delta\rho/\rho). \quad (10)$$

To enhance the helium abundance to $Y = 0.26$ on the $10^6 M_\odot$ scale requires $\delta\rho/\rho \sim 0.1$ on this scale, which means $\delta\rho/\rho$ on the $10^6 M_\odot$ scale will become nonlinear at $z \sim 100$. This cannot be realized in the standard cold dark matter (CDM) model, in which structures on this scale become non-linear at $z \lesssim \mathcal{O}(10)$ [49], but may be possible in models where primordial seeds such as topological defects provide nonlinear fluctuations on small scales [50–52]. A $\delta\rho/\rho$ of 0.1 at $z \sim 1000$ with $\sim 10^6 M_\odot$ scales would correspond to fluctuations in the microwave background radiation on scales that are less than 8 arc minutes and thus would be smoothed by the finite size of the surface of last scattering.

In models that generically form $\sim 10^6 M_\odot$ cold clouds in proto-galaxies [56,57], a higher helium content may arise if Pop II stars form in the shock waves from the first generation supernovae in the cloud (simplified in Figure 3) [58]. The temperature of these clouds can stay around 10^4K for a long time due to a sharp drop in the cooling function of the gas cloud at 10^4K [48]. If a strong UV photon background exists (which is likely due to the presence of supernovae shocks), hydrogen can be partially ionized at this temperature and interact primarily with the UV photons in the cloud, but helium remains mostly neutral and interacts primarily with atoms, ions and electrons. The sound speed in helium, c_{He} , is then $\sim 10\text{ km/sec}$ (for a temperature of $\sim 10^4\text{K}$), while the sound speed in hydrogen, c_{H} , can be

much larger. When the velocity of a supernova shock wave drops below c_H , the shock no longer compresses hydrogen in the cloud into the shock front but continues to do so with helium. The enhanced helium abundance is then [7]

$$Y \approx \frac{Y_p M_{\text{sh}}}{(1 - Y_p) M_{\text{tot}} \delta / l + Y_p M_{\text{sh}}}, \quad (11)$$

where M_{sh} is the mass swept by the shock, M_{tot} is the total mass of the cloud, Y_p is the helium abundance before the shock, δ is the thickness of the shock front and l is the thickness of the cloud after being compressed by the shock wave. If the SNe rate is $\gtrsim 10^{-6} \text{ yr}^{-1}$ per cloud, the shock wave can propagate through the entire cloud at a speed larger than c_{He} [7,40]. Then $M_{\text{sh}} \sim M_{\text{tot}}$. If $l \gg \delta$, i.e., the density inside the shell is much higher than the density outside, Y can be significantly larger than Y_p . Therefore stars formed from the compressed gas at the shock front may have a higher helium abundance than the primordial value.

We have briefly discussed several scenarios to enhance the helium abundance in GCs. There may be other possible scenarios, such as a magnetic field, that may also segregate ionized gas from neutral gas. If these scenarios operate primarily in GCs, they will not have a direct effect on HII regions where the primordial helium abundance is measured, nor will they affect the helium abundances in galactic disks. Helium-enriched stars from disrupted GCs may only constitute a small population of halo stars. Therefore, there may not be evidence in disk stars that support helium enhancement processes. Only more refined stellar evolution models and GC observations can better determine the helium abundance in GCs. Once again, a spread in Y after these helium enhancement processes may be a candidate to account at least in part for the spread in age estimates for different GCs which assume a universal Y .

V. THE UNCERTAINTY IN MASS LOSS

Possible mass loss near the turn-off region of GCs is another uncertainty that affects the age estimate of GCs [7,8,59]. It is motivated by the closeness of GC turn-off temperatures

and the small temperature range $6600 \pm 200 \text{K}$, where Pop I F-type stars are observed to have severely depleted lithium abundances (the so-called lithium dip) [60,61]. One explanation of the lithium dip is an instability strip induced mass loss [62].

Lithium burns rapidly at temperatures above $2.5 \times 10^6 \text{K}$. It is therefore completely destroyed at layers with temperatures above $2.5 \times 10^6 \text{K}$ [63]. At the temperature range of F stars in which the lithium dip occurs, the base of a star's outer convective zone cannot reach this lithium-burning temperature. Therefore, its surface lithium abundance should be its primordial value (although some negligible depletion occurs in the pre-main sequence [64]). The mass loss at the surface, however, leads to a deeper penetration of the convective layer into the star's radiative interior. When the convective zone reaches down to layers with no lithium, the surface lithium abundance can be depleted due to mixing [62,65]. The shape of the observed lithium dip on the $[\text{Li}/\text{H}]$ -Temperature plane can be reproduced quite well in the mass loss mechanism with a mass loss rate [62]

$$\dot{M} \gtrsim 7 \times 10^{-11} M_{\odot} \text{yr}^{-1}. \quad (12)$$

But the narrowness of the observed Pop I lithium dip constrains any significant mass loss to a restricted temperature range between 6500K and 6700K. On the other hand, the absence of a severe beryllium depletion in this temperature range in Pop I stars limits any mass loss rate to [62]

$$\dot{M} \lesssim 1 \times 10^{-10} M_{\odot} \text{yr}^{-1}, \quad (13)$$

which coincides with the limit from observations on ionized stellar winds of F type main sequence stars [66]. Alternative explanations of the lithium dip include radiative diffusion [67], and rotation-induced mixings that leads to a more extensive of mixing between the surface lithium and the depleted lithium in the radiative interior [68].

The same instability strip which may induce mass loss in Pop I F-type stars may also operate in Pop II stars in a similar temperature range, 6500–6700K. These stars generally have an undepleted lithium layer of about $0.04 M_{\odot}$ at ZAMS. Given a maximal lifetime of

several Gyr they spend in the temperature range, Dearborn *et al.* have shown that if the mass loss rates are $\gtrsim 10^{-11} M_{\odot}/\text{yr}$, it should produce a similar lithium dip in Pop II stars [69]. Several halo stars in the vicinity of this temperature range have been observed to have depleted lithium, but the existence of a lithium dip in Pop II stars is still far from established [70]. It is to be noted, however, that even an absence of the lithium dip in Pop II stars doesn't automatically exclude the instability strip induced mass loss, as long as the mass loss rates are $\lesssim 10^{-11} M_{\odot}/\text{yr}$. This instability strip induced mass loss does not affect the lower main sequence and so avoids the arguments against large-scale mass loss throughout the entire lower main sequence [62].

The position of the instability strip on the Pop II main sequence is quite uncertain. If mass loss operates in stars in the Pop I lithium dip, by a simple extrapolation, mass loss may also operate in a similar temperature range around 6500–6700 K, which is in the vicinity of the turn-off temperature of GCs [8]. Observations of low metallicity blue stragglers, on the other hand, seems to indicate that the instability strip is bluer than the turn-off point of GCs with similar metallicities [71]. However, blue stragglers may be too pathological to draw conclusions on the main sequence of GCs.

Another justification for instability strip induced mass losses in the turn-off region of GCs may come from the red edge of RR Lyrae stars and the calculated dependence of this red edge on Y (the envelope helium abundance), Z (the metallicity), M (the mass) and L (the luminosity). Observations of RR Lyrae stars found the red edge of the instability strip in HB stars lies at $\log T_{\text{e}} \sim 3.81$ for M15 and $\log T_{\text{e}} \sim 3.79$ for M3. Although there hasn't been a theoretical calculation of the position of the instability strip for Pop II stars, it has been shown for Pop I cepheids [72]

$$\begin{aligned} \log T_{\text{FRE}} = & (\text{const.} + 0.106Y) + (0.163 - 0.392Y - 0.592Z) \log(M/M_{\odot}) \\ & + (-0.074 + 0.074Y - 0.437Z) \log(L/L_{\odot}), \end{aligned} \quad (14)$$

where T_{FRE} is the effective temperature of the fundamental red edge. If we take eq. (14), and take $Y_{\text{HB}} \approx 0.25$, $Z < 10^{-3}$, $M/M_{\odot} \approx 0.65$ for RR Lyrae stars, $Y \lesssim 0.1$ [13,26], $M/M_{\odot} \approx 0.75$ for main sequence turn-off stars, and $L_{\text{RR}}/L_{\text{TO}} \approx 1.4$ [1], we get $\log T_{\text{FRE}}(\text{RR}) - \log T_{\text{FRE}}(\text{TO}) \approx -0.05$. Therefore, the instability strip at the main sequence turn-off luminosity has a red edge of $\log T_{\text{FRE}} \sim 3.85$, which is very close to the turn-off region of metal-poor globular clusters ($T_{\text{e}} \sim 3.80$ to 3.83 [13,26]). It is therefore conceivable that a consistent instability strip calculation for Pop II stars can extend the instability strip to the turn-off region. In this regards, theoretical calculations of the instability strip for Pop II stars are necessary to extrapolate the red edge accurately from RR Lyrae stars down to the turn-off luminosity.

When mass loss occurs at the temperature of the turn-off, the small reduction in mass causes the model to turn off at a lower luminosity with respect to models without mass losses, since the turn-off luminosity of a main sequence Pop II star decreases as the mass of the star decreases [8,59]. Stars also appear to spend an increased fraction of their life beyond the turn-off (since less massive stars always evolve slower than more massive ones) [8]. The GCs will then (incorrectly) appear older due to their lower turn-off luminosities, according to eqs. (1), (2) and (5) [8,59].

Several authors [7,8] have calculated the effect of a mass loss rate $\sim 10^{-11} M_{\odot} \text{ yr}^{-1}$ in the temperature range of $6500 \pm 200\text{K}$ and $6600 \pm 200 \text{ K}$ on the evolution of GCs. Such assumptions result in GCs of 11 Gyr to 13 Gyr old looking $2 \sim 3$ Gyr older. To see the effect of the mass loss on our helium diffusion models, we repeated our model calculations in section 2 with a mass loss rate

$$\dot{M} = 10^{-11} M_{\odot} \text{ yr}^{-1} \exp\left[-\left(\frac{T - 6500\text{K}}{240\text{K}}\right)^2\right], \quad (15)$$

for both $Y = 0.24$ and $Y = 0.28$. Figure 4 shows the resultant turn-off visual magnitude vs. age relation for different cases. We find that a mass loss rate of eq. (15) will only affect

isochrones younger than ~ 12 Gyr for $Y = 0.24$ and ~ 15 Gyr for $Y = 0.28$ significantly, decreasing their turn-off visual magnitude to the level of about 1 Gyr older isochrones without mass loss. Therefore, for a GC age of 14–15 Gyr by conventional estimates, or about 11–12 Gyr if assuming $Y = 0.28$, the decrease in age due to a mass loss rate of eq. (15) alone is at most ~ 1 Gyr. This age reduction due to mass loss is smaller than the 2–3 Gyr reduction calculated previously from stellar models without helium diffusion [7,8]. The reason may lie in that in helium diffusion models, mass loss can strip the outer helium-poor layer of stars and thus reduce the effect of helium diffusion on stellar evolution. For example, a $0.8M_{\odot}$ low- Z model with no mass loss has a surface helium abundance of less than 3% at turn-off due to helium diffusion, but a similar model with a mass loss of eq. (15) has a surface helium abundance of more than 20%.

Since it has been shown that a high helium abundance of 0.28 can decrease the age estimate for GCs from ~ 14 Gyr to about 11 Gyr, from figure 4 it can be seen that a combination of $Y = 0.28$ and a mass loss rate like that in eq. (15) can further decrease the GC age to as low as 10 Gyr. However, to what extent the mass loss mechanism can lower the age estimate of GCs is not only determined from its turn-off magnitude-age relation but also constrained by the calculated GC luminosity function under mass loss compared with observations [8,65].

It has been pointed out that mass loss near the GC turn-off point can significantly affect the luminosity function of GCs, since the longer life time that stars spend after their turn-off due to mass loss results in a bump on the LF in the subgiant region [8,65]. In figure 5(a) and 5(b), we plot the predicted luminosity functions of GCs with a mass loss rate of eq. (15) (assuming a Salpeter initial mass function [45]) for both $Y = 0.24$ and $Y = 0.28$, compared with observations compiled by Stetson [73]. For $Y = 0.24$, figure 5(a) shows that a 12 Gyr mass loss LF can be ruled out by the absence of any large size bump at the subgiant region in the observation, but a 13 Gyr mass loss LF may still be allowed. For the $Y = 0.28$ case, figure 5(b) shows that the 11 Gyr mass loss LF can be confidently ruled out, but the 12 Gyr mass loss LF may not be ruled out easily. Therefore, due to the constraint from the

luminosity function of GCs, mass loss essentially cannot lower the age of GCs to below 12 Gyr even when combined with a high helium abundance. This result should also hold if we consider oxygen-enhancement in GCs, or if we use another power-law initial mass function, since it has been shown that the LFs of GCs in the turn-off and subgiant region are not sensitive to both of the two factors [73].

It is interesting to note from figure 5(a) and (b) that mass loss can improve the fit at the red giant region of LF between models and observations. But it may be premature to draw any conclusion from comparison to this uncertain portion of the data.

Isochrone fittings also seem to indicate that even with a combination of high Y and mass loss, an age lower than 12 Gyr is hard to reach. Figure 6 shows $Z = 0.0002$ isochrones with eq. (15) and $Y = 0.28$ at 12 and 13 Gyr old, overlaid on the fiducial sequence of NGC6397, as well as a standard isochrone without mass loss and with $Y = 0.24$ at 15 Gyr (the same one as in Fig. 2). Clearly, an isochrone in between 12 Gyr old and 13 Gyr old with $Y = 0.28$ and mass loss may fit the observation acceptably (while the 12 Gyr isochrone with $Y = 0.28$ and no mass loss fits fairly well in figure 2). Therefore, effects of a higher Y and a mass loss on GC ages do not add up linearly in the isochrone fitting method, and an GC age lower than 12 Gyr seems still unachievable.

Applying our mass loss calculations to Pop II stars, we find that with a peak mass loss rate of $10^{-11} M_{\odot} \text{ yr}^{-1}$, severe lithium depletions occur at stars between $\sim 0.8 M_{\odot}$ and $\sim 1.0 M_{\odot}$ (similar to the conclusion of Dearborn *et al.* [69]). Therefore, in isochrones older than ~ 14 Gyr for $Y = 0.24$ or older than ~ 12 Gyr for $Y = 0.28$, no stars with lithium severely depleted from mass loss will be observed since they already evolved away from the red giant branch. That is, if further observations find no evidence for a mass loss induced lithium depleted in Pop II stars, it may simply indicate that our universe is too old for those lithium depleted Pop II stars (if there were any) to survive. In isochrones younger than these ages, lithium-depleted stars should be observed in either their main sequence, subgiant or giant phase. It should be noted that a difference in mass loss rates may exist between globular clusters and field stars if only the helium abundance in globular clusters is

enhanced, since a higher helium abundance increases the surface temperature of stars and therefore shifts the relative position of the instability strip in isochrones.

VI. SUMMARY

As we have seen, the possible systematic uncertainties in the helium abundance of globular clusters and an instability strip induced mass loss near the turn-off region of globular clusters allow an average age of globular clusters as low as $\sim 20\%$ below current estimates. Therefore the currently quoted age estimate of 14.1 ± 1.5 Gyr [1] or 15 ± 1.5 [2] is potentially subject to systematic shifts and its uncertainties are model dependent and not fully represented by the quoted error. Based on eq. (5) and our mass loss calculations, we recalculated the age of five metal-poor clusters using data compiled by Sandage [1] for four cases with and without oxygen-enhancement. Tabulated in table 1, the resultant average ages range from 11.3 ± 1 Gyr to 14.6 ± 1.5 Gyr for the four cases, compared with 14.1 Gyr from Sandage's estimate assuming a primordial helium abundance, no mass loss, no helium diffusion and oxygen-enhancement. In table 1, oxygen-enhancement is approximated by models with solar-scaled abundances that satisfy eq. (6) [25]. In case (iv), the constraint from the luminosity function of globular clusters on mass loss holds true with and without oxygen-enhancement, and constrains the age of globular clusters to be older than ~ 12 Gyr in both cases.

It is unlikely that all globular clusters will have an enhanced Y of 0.28, given the current inferences of the helium abundance in globular clusters. An average Y of 0.26, for example, is more compatible with available helium inferences. In all cases, however, after uncertainties in the helium abundance, mass loss, helium diffusion and oxygen enhancement are considered, and the $\sim 10\%$ uncertainty from calibrations of RR Lyrae stars is included, the lowest age estimate for globular clusters seems to be about 10 Gyr.

Clearly, the true accuracy of globular cluster age estimates would benefit from better estimates of non-canonical effects in stellar models and better determinations of mass losses

in Pop II stars. In inferring the helium abundance, stellar model comparisons with observed GC parameters should include non-canonical effects such as helium diffusion, core rotation, etc. The existence of an instability strip induced mass loss near the turn-off region can be explored by the further observations of the luminosity functions of globular clusters and lithium observations in Pop II stars.

A globular cluster age of 11 ± 1 Gyr is entirely consistent with the age of the beginning of nucleosynthesis of heavy elements (i.e., SNe events) measured by radioactive dating that gives a lower limit of 10 Gyr [74,75]. It is also consistent with the age of the galactic disk, 10 ± 2 Gyr, measured from the cooling of white dwarfs [76], provided that the disk collapsed from the halo within 1 to 2 Gyr.

If globular clusters are indeed 11 ± 1 Gyr old, a universe as young as 11 Gyr is then possible if globular clusters formed at redshift $z \gtrsim 4$. This will significantly relax the current constraints on cosmological parameters. For a baryonic universe where $0.01 \lesssim \Omega \lesssim 0.1$, the Hubble constant can be as high as 90 km/sec/Mpc; for non-baryonic dark matter universes with $\Omega > 0.3$, $H \lesssim 77$ km/sec/Mpc; if $\Omega = 1$, $H = 60$ km/sec/Mpc. To turn the problem around, if the measurements of the Hubble constant eventually converge, it will put constraints on Ω in a $\Lambda = 0$ Friedman-Robertson-Walker universe and improve our understanding of the age of globular clusters.

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TABLE I. The age estimates from eq. (5) and our mass loss calculations for five metal-poor globular clusters. *All ages suffer an additional $\sim \pm 10\%$ uncertainty from the $\sim \pm 0.1$ magnitude uncertainty in the calibration of RR Lyrae stars.*

Clusters	Case (i) ^a	Case (ii) ^b	Case (iii) ^c	Case (iv) ^d
[O/Fe]=0				
M68	12.5 Gyr	11.3 Gyr	10.2 Gyr	
M92	16.2 Gyr	14.6 Gyr	13.2 Gyr	
NGC6397	15.5 Gyr	14.0 Gyr	12.7 Gyr	
M15	14.5 Gyr	13.1 Gyr	11.8 Gyr	
M30	14.3 Gyr	12.9 Gyr	11.7 Gyr	
Average				
[O/Fe]=0	14.6 Gyr	13.2 Gyr	11.9 Gyr	$\gtrsim 12$ Gyr
[O/Fe]=0.6	13.9 Gyr	12.5 Gyr	11.3 Gyr	$\gtrsim 12$ Gyr

^a $Y = 0.24$, no mass loss; ^b $Y = 0.26$, no mass loss; ^c $Y = 0.28$, no mass loss; ^dan enhanced Y and an instability strip induced mass loss according to eq. (15).

Figure Captions

Figure 1. Two isochrones with similar parameters but different mixing lengths.

Figure 2. Isochrones with and without an enhancement of the helium abundance in GCs compared with the fiducial sequence of NGC6397 ($[\text{Fe}/\text{H}] \approx -2$) (denoted by triangles). The $Y = 0.24$ isochrones are shifted by $E(B - V) = 0.11$ and $m - M = 12.35$; the $Y = 0.28$ isochrone is shifted by $E(B - V) = 0.14$ and $m - M = 12.45$.

Figure 3. The propagation of a SN shock front inside a $10^6 M_\odot$ cloud.

Figure 4. The calculated turn-off magnitude-age relation for different isochrones. Comparisons can only be made between curves with similar Y , since different Y 's yield different ZAHB luminosities.

Figure 5. The calculated luminosity functions for GCs compared with observations [73]. N is the number of stars in each 0.2 magnitude bin. The reference point is defined as the point on main sequence that is 0.05 mag redder than the turn-off. (a) $Y = 0.24$; (b) $Y = 0.28$. Mass losses are calculated assuming a mass loss rate of eq. (15). The sharpness of the bump in subgiant regions is due to the finite grid of stellar models.

Figure 6. Isochrones with and without a higher helium abundance and mass loss, compared with the fiducial sequence of NGC6397 ($[\text{Fe}/\text{H}] \approx -2$) (denoted by triangles). The 15 Gyr isochrone with $Y = 0.24$ and no mass loss is shifted by $E(B - V) = 0.11$ and $m - M = 12.35$; the 12 and 13 Gyr isochrones with $Y = 0.28$ and a mass loss rate that satisfies eq. (15) are shifted by $E(B - V) = 0.14$ and $m - M = 12.38$.